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Research Article

A Novel Clustering Solution Based on Energy Threshold for Energy Efficiency Purposes in Wireless Sensor Networks

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Abstract: In many wireless sensor network (WSN) applications, nodes are randomly deployed and self-organize into a wireless network to perform tasks. In practice, recharging the batteries of network nodes after deployment is often difficult. Network nodes often operate autonomously, so the main focus is on increasing the node lifetime. Data redundancy is another limitation that makes nodes inefficient. In most cases, densely deployed nodes in a monitoring area will have redundant data from neighboring nodes. Therefore, we propose a clustering technique to select the Cluster Head (CH) node in small-scale WSNs. Since transmission consumes more energy than data collection, this protocol enables reactive routing, where transmission occurs only when a certain threshold is reached. In addition, based on their heterogeneous energy levels, nodes can be grouped into three categories: Normal, Intermediate, and Advanced. Simulation results in MATLAB/Simulink show that, after approximately 3000 rounds, the proposed method successfully transmitted about 3.1×10^4 packets to the base station, compared to 2.3×10^4 packets for the Low Energy Adaptive Clustering Hierarchy (LEACH) protocol. In addition, the time when the last node died was approximately 3,500 rounds, whereas the LEACH protocol only maintained about 1,500 rounds. The results have shown the effectiveness of this technique in reducing the dead node rate and increasing packet transmission efficiency.

Keywords: Cluster head selection; Energy-aware clustering; Energy-efficient protocol; Reactive routing protocol; Small-scale sensor networks; Threshold-based data transmission; Wireless sensor networks; WSN lifetime optimization.

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1. Introduction

Wireless Sensor Network (WSN) consists of numerous compact and cost-efficient sensing devices capable of communicating wirelessly. These devices, or sensor nodes, are typically deployed randomly in a given area to monitor environmental parameters. After capturing data from their surroundings, the sensor nodes process and forward this data to neighboring nodes, ultimately reaching a central collection point [1], [2]. A WSN generally includes at least one Sink node, which possesses greater computational power, communication capabilities, and energy resources than regular nodes. Moreover, WSNs support both intra-network communication between sensor nodes and external communication with end users, as illustrated in Figure 1 [3]–[8].

The applicability of WSNs spans a wide array of domains. These networks are integrated into systems for medical measurements, infrastructure crack detection, chemical radiation monitoring, and agricultural monitoring of soil and plant nutrients. They also play a critical role in natural disaster detection systems. Such diverse implementations demonstrate the significance of WSNs not only in civilian applications but also in military and security contexts [9]–[16].

Despite their extensive utility, WSNs are continually challenged by various scientific, engineering, and technological limitations. One of the most pressing issues is the energy constraint. Sensor nodes are designed to be compact, and consequently, their embedded batteries have limited capacity. This limitation significantly reduces the operational lifetime of the network [17], [18]. Furthermore, although sensor nodes must transmit substantial amounts of data, their constrained energy budgets limit the communication distance between nodes, requiring efficient communication protocols.

A substantial body of research has been devoted to developing energy-saving mechanisms tailored for WSNs in recent years [19]–[21]. For instance, Rault et al. [22] proposed several energy-saving strategies aimed at extending the overall network lifespan by optimizing communication and processing loads (see Figure 2). One of the most effective approaches involves the formation of energy-efficient clusters, which inherently reduce transmission power but also limit the communication range.

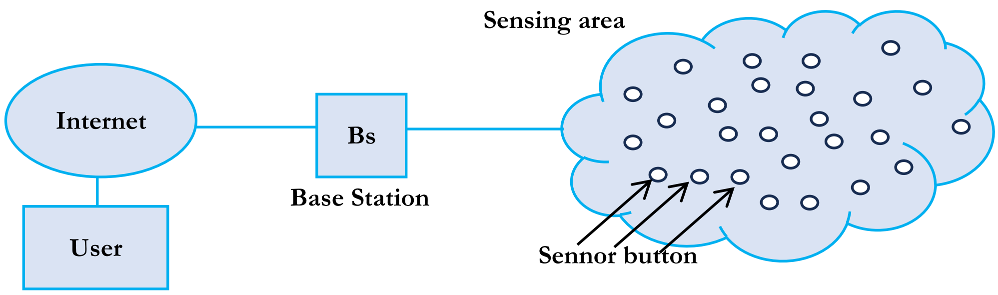


Figure 1. Overview of WSN.

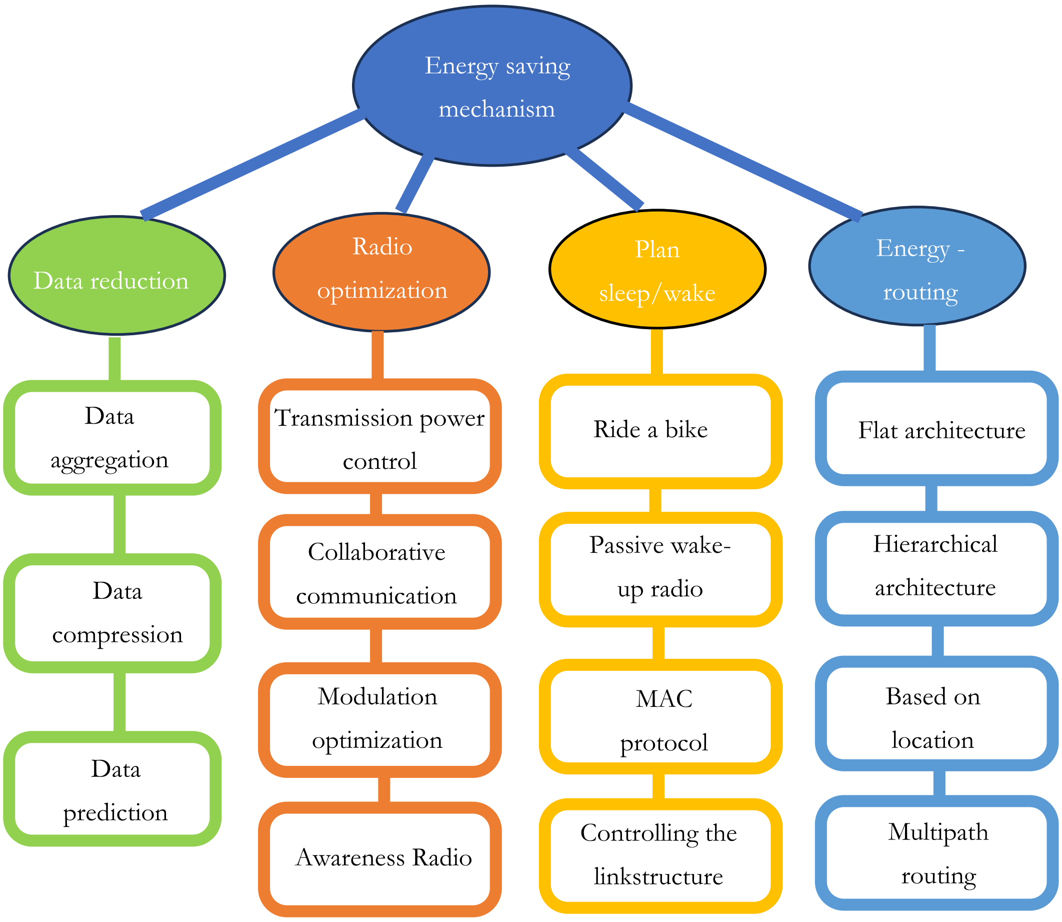


Figure 2. Classification of energy-saving mechanisms.

In this context, cluster heads (CHs) play a central role. A CH is selected from among sensor nodes to aggregate, compress, and manage the data from its surrounding cluster members. It is responsible for performing energy-intensive tasks such as data reduction and scheduling communication. Once data aggregation is completed and transmitted, the CH can trigger sleep modes in member nodes to further conserve energy [23]–[25]. These mechanisms form the foundation for many advanced WSN protocols that aim to balance energy consumption and extend network lifetime.

The rest of the paper is organized as follows. Section 2 presents the related work. Section 3 introduces the proposed clustering protocol and cluster head selection mechanism. Section 4 describes the simulation results and their analysis. Finally, Section 5 concludes the paper and outlines future research directions.

2. Related Works

Low Energy Adaptive Clustering Hierarchy (LEACH) [26] remains one of the most popular routing algorithms used for WSNs. However, this technique assumes the highest concurrent capacity and does not consider the transmission threshold. In some other works, the Stable Election Protocol [26] performs hierarchical classification of nodes in the network to reflect energy heterogeneity. One limitation of this approach is the unnecessary energy consumption for periodic data transmission. The Threshold Sensitive Energy Efficient Sensor Network [27] method is based on a threshold data transmission mechanism, but it only uses a homogeneous network. Therefore, this technique has several limitations related to the actual energy distribution of nodes in the network. Another notable clustering protocol proposed by Younis et al. [28] is a cluster head (CH) selection method that is performed periodically (Hybrid Energy-Efficient Distributed Clustering). This proposed method is based on factors such as remaining energy level, number of neighbors, distance to nodes. The limitation of the proposed method is the requirement of repeated control exchanges, which causes delay and complexity in small-scale networks. There are not many protocols that integrate both optimally; previous protocols have focused on thresholding or heterogeneity. In particular, incorporating the energy factor is one of the important issues to consider.

A novel energy threshold-based clustering solution is proposed for small-scale wireless sensor networks that fully integrates all three elements: reactive communication, three-level heterogeneous energy, and a dynamic cluster head selection mechanism (based on the conditional probability of energy threshold). This method aims to optimize energy efficiency while im-proving the lifetime of nodes in the network.

3. Proposed Method: Clustering Protocol and CH Selection

3.1. Low Energy Adaptive Clustering Hierarchy Protocol

One of the most popular algorithms to improve the overall performance of WSNs is the Low-Energy Adaptive Clustering Protocol. With the ability to self-organize and self-adapt, this algorithm is an adaptive clustering protocol. This protocol assumes that the sensor nodes can sense the surrounding environment and can communicate with each other. In addition, the sensor nodes are similar, have fixed locations, and have limited energy[29], [30]. Figure 3 illustrates the stages of the Low-Energy Adaptive Clustering method. Clusters are created in the setup phase, and then data is transmitted in the steady-state phase.

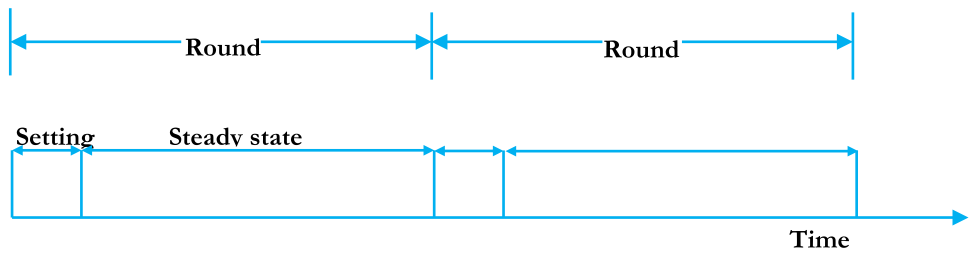


Figure 3. Small-scale WSN with randomly deployed network nodes.

The threshold function for selecting cluster heads (CHs) in each round is defined in Equation (1).

$$T(n) = \begin{cases} \dfrac{P}{1 - P * \left(r mod \dfrac{1}{p}\right)} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where G is the collection of nodes that were not CHs in the previous $1/p$ rounds, r is the current round, and p is the proportion of CHs in the network's total number of nodes. $T(n) = 1$ will be the threshold value after $1/p - 1$ rounds, at which point all nodes can once more become CHs.

Based on the Carrier Sense Multiple Access (CSMA) protocol, each selected CH will send a message and broadcast to the remaining nodes in the network. Each node will select a CH and send the result of its cluster head selection. All CHs must maintain the receiver in the active state (on state) during this process. Then, each CH, based on the number of nodes in the cluster after they are formed, allocates separate time slots to each node.

In their allocated time slots, nodes transmit their sensor data to the CH (the process of collecting and sending data in the steady-state phase). The CH receives all the data and aggregates it before forwarding the data. Then, the network will continue the setup and steady-state phase to initiate a new cycle. The low-power adaptive clustering protocol assumes a simple radio model that describes the power dissipation through electronics, transmitters, power amplifiers, and receivers.

The radio model used to study the low-power adaptive burst protocol is shown in Figure 4. The figure illustrates the energy consumption during data transmission and reception over a wireless medium. In the transmitter, the total energy consumed to transmit a packet over space consists of two main components: First is the fixed energy for processing coding, modulation and circuit operation, which is proportional to the packet size; Second is the energy to overcome the path loss, which depends on the distance d and the environmental attenuation coefficient. In the receiver, the Energy Consumption to receive a packet only includes the energy for demodulation, decoding, and packet processing.

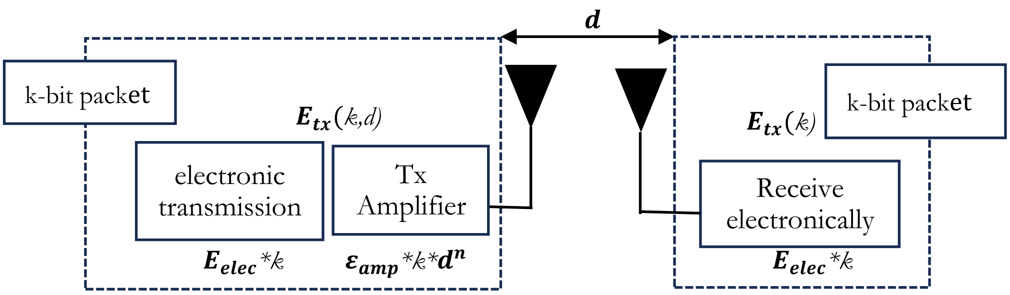


Figure 4. Energy consumption model in wireless communications.

3.2. Selecting stable CH based on threshold

The proposed method in this study is developed by combining three critical aspects: a threshold-based transmission mechanism, a heterogeneous energy model among sensor nodes, and the ability to respond to environmental variations dynamically. This integration enables a more energy-efficient clustering strategy than traditional methods such as the LEACH Protocol, particularly in small-scale WSNs where resources are significantly constrained.

The method supports reactive routing, in which nodes transmit data only when certain thresholds are triggered, avoiding unnecessary communication. Since data transmission consumes considerably more energy than sensing, this strategy significantly extends node lifetime. In this model, nodes are classified into three types according to their energy levels: normal nodes, intermediate nodes, and advanced nodes. The energy of normal nodes is denoted as E_o, while intermediate and advanced nodes have increased energy levels defined as $E_{INT} = E_o(1 + \mu)$ and $E_{ADV} = E_o(1 + \alpha)$, respectively. The intermediate energy factor μ is assumed to be half of α , i.e., $\mu = \alpha/2$.

If n is the total number of nodes in the network, m is the fraction of advanced nodes, and b is the fraction of intermediate nodes, then the total energy of all nodes can be expressed in Equation (2).

$$E_{total} = nE_o(1 + m\alpha + b\mu \tag{2}$$

which accounts for the heterogeneity in energy distribution among node types.

To ensure a fair and balanced selection of cluster heads (CHs), each node type is assigned a distinct probability of becoming a CH. These are adjusted based on energy contribution. The probability for normal nodes is given by Equation (3). For intermediate and advanced nodes, the probabilities are proportionally higher, as shown in Equations (4) and (5), respectively.

$$p_{nrm} = \frac{p_{opt}}{1 + m.\alpha + b.\mu} \tag{3}$$

$$p_{int} = \frac{p_{opt}.(1 + \mu)}{1 + m.\alpha + b.\mu} \tag{4}$$

$$p_{adv} = \frac{p_{opt}.(1 + \alpha)}{1 + m.\alpha + b.\mu} \tag{5}$$

Each node in the network independently generates a random value between 0 and 1 to determine whether it becomes a CH. If the generated number is less than a dynamically computed threshold, the node assumes the CH role. These threshold values are computed using a modified version of the LEACH formula, adapted for heterogeneous networks. The threshold for each node type is expressed in Equations (6) to (8):

$$T_{nrm}(n) = \begin{cases} \dfrac{p_{nrm}}{1 - p_{nrm}\left\{r \bmod \dfrac{1}{p_{nrm}}\right\}} & \text{if } n_{nrm} \in G_n \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

$$T_{int}(n) = \begin{cases} \dfrac{p_{int}}{1 - p_{int}\left\{r \bmod \dfrac{1}{p_{int}}\right\}} & \text{if } n_{int} \in G_i \\ 0 & \text{otherwise} \end{cases} \tag{7}$$

$$T_{adv}(n) = \begin{cases} \dfrac{p_{adv}}{1 - p_{adv}\left\{r \bmod \dfrac{1}{p_{adv}}\right\}} & \text{if } n_{adv} \in G_a \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

In these expressions, r is the current round, and G_n, G_i, and G_a denote the set of normal, intermediate, and advanced nodes that have not been CHs in the last $1/p$ rounds. The protocol ensures that the average number of CHs per round is approximately constant and equal to $n.\ p_{opt}$ as defined in Equation (9).

$$n.(1 - m - b).p_{nrm} + n.b.p_{int} + n.m.p_{adj} = n.p_{opt} \tag{8}$$

At the beginning of each round, the clusters are reset. In this protocol, at the time of changing clusters, the following parameters are transmitted including:

- Attributes (A): The physical parameters over which the information is being sent.
- Reporting Interval (RI): The time interval between consecutive messages sent from a node.
- Hard Threshold (HT): The attribute sensor's absolute value above which the node will send data to the CH.
- Soft Threshold (ST): The minimum sensed value at which nodes initiate transmission through the transmitter

The sensor nodes continuously sense the parameters of the surrounding environment. When the parameters in the attribute set reach the hard threshold value, the transmitter is activated, and the data is sent to the CH. The sensor value is an internal variable in the node that holds this sensor value. The nodes only transmit data in the remaining time intervals when the sensor value exceeds the hard threshold, or when the difference between the current sensor value and the value stored in the sensor value variable reaches or exceeds the soft threshold. Therefore, the number of data transmissions can be reduced based on these thresholds. When the value changes little, the soft threshold stops transmitting, which reduces the number of subsequent signal transmissions. The performance metrics used in the simulation are:

- The steady-state period is the time elapsed from the start of the network until the first node ceases to operate.
- The unstable period spans from the death of the first node to the death of the last node, encompassing both the number of live nodes and the number of dead nodes in each round.

4. Simulation Results

To evaluate the performance of the proposed energy-efficient clustering protocol, simulations were conducted using MATLAB/Simulink. This section presents the experimental setup, parameter configurations, and a comparative analysis between the proposed method and the LEACH protocol. The goal is to measure the effectiveness of the protocol in terms of energy consumption, packet delivery, and node lifetime. Table 1 presents the simulation parameters used for modeling the WSN. These include network dimensions, initial node energy, and energy consumption settings for transmission, reception, and data aggregation.

Table 1. Parameters and values of the simulated WSN model.

Parameters	Value
Spatial size of the network	100m*100m
Number of buttons	120
Initial energy of the node	0,5J
Energy transmission	50 nJ per bit
Energy received	50 nJ per bit
Free space amplifier power	10 pJ per bit per m2
Data aggregation power	5 nJ per bit
Packet size	6400bit

The network configuration and energy model for WSN simulation, along with the corresponding parameters, are detailed in Table 1. The network is small-scale (100m × 100m) with 120 randomly distributed nodes and a limited energy supply. This set of parameters provides a quantitative basis for accurately calculating the energy consumption when transmitting or receiving packets between nodes or to the cluster head (CH), thereby evaluating the energy efficiency and network lifetime in realistic conditions. Figure 5 illustrates the spatial distribution of nodes and the location of the sink node used in the simulation.

Figure 5 shows the small-scale WSN model used in the simulation. The sensor nodes are randomly distributed in a monitoring area (100m x 100m). A total of 120 nodes are deployed, with the base station placed outside the sensing area, allowing the routing efficiency and energy efficiency of the proposed protocol to be evaluated under near-realistic conditions. Simulations are performed with parameter values of $a = 1$ and $m = 0.5$ and $b = 0.3$. These tuning parameters will affect the network's stability, lifetime, and bandwidth. With the LEACH protocol, the network energy drops linearly and rapidly, indicating that all nodes continuously transmit data regardless of whether there is important information or not. This results in high energy consumption at the early stage and reduces the network lifetime (Figure 6).

Although the energy is rapidly depleted, the low-power adaptive clustering protocol still ensures packet delivery to multiple nodes (without concentrating on a single node). In addition, the network maintains continuous operation, nodes are always ready to transmit data, making it suitable for applications that require continuous updates. Figure 7 shows a comparison of the number of packets received by the base station in each round between the low-power adaptive clustering method and the threshold-based stable CH selection method. Simulation results in MATLAB/Simulink show that, after approximately 3000 rounds, the proposed method successfully transmitted about 3.1×10^4 packets to the base station, compared to 2.3×10^4 packets transmitted by the LEACH protocol.

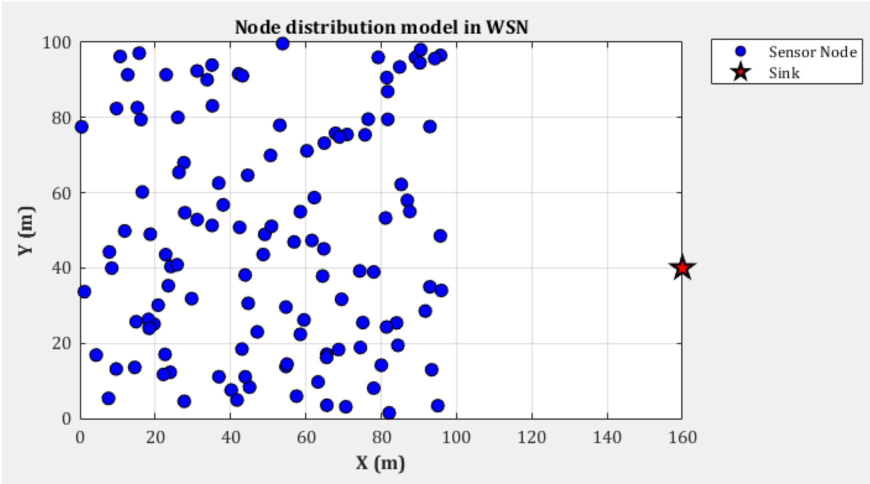


Figure 5. Simulation results of a small-scale WSN with randomly deployed network nodes

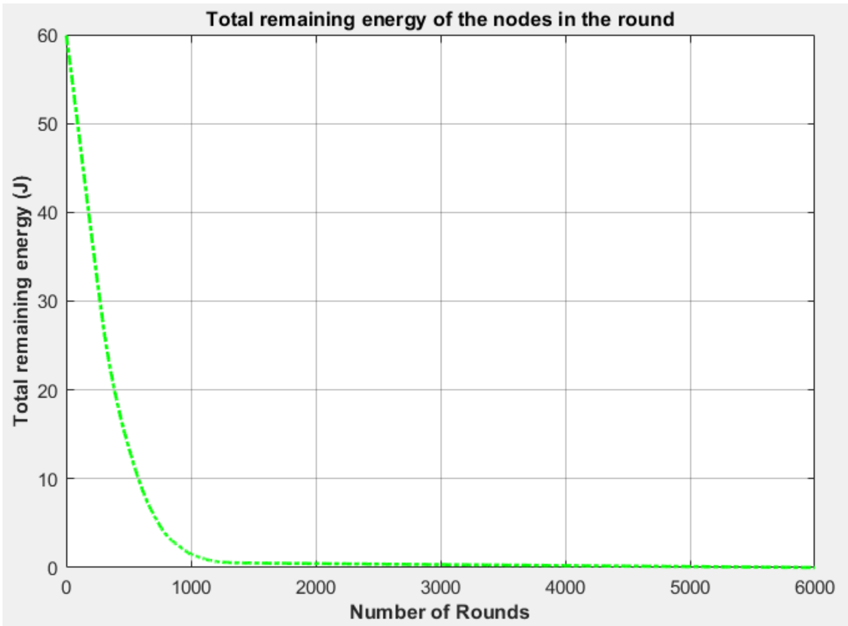
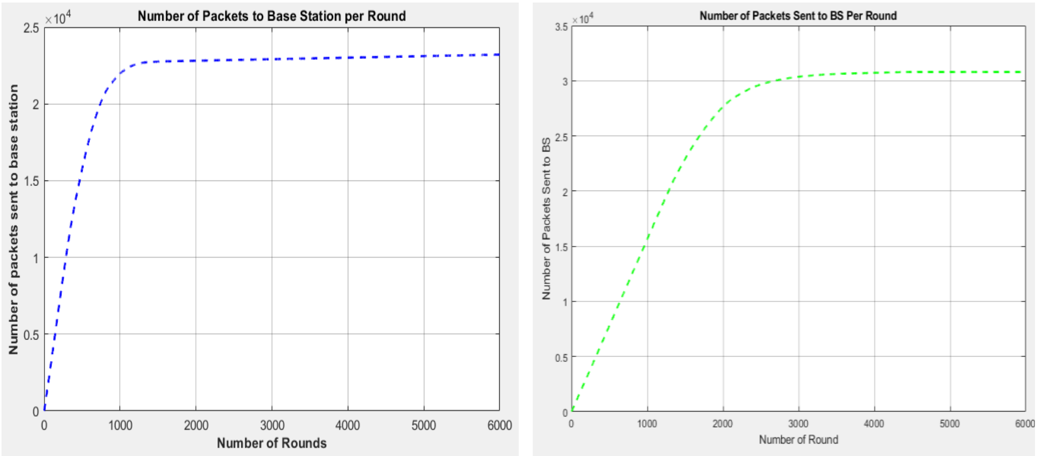


Figure 6. Total residual energy of nodes in each round.

The low-power adaptive clustering protocol (Figure 7a) does not limit the frequency of packet transmission, ensuring high throughput and making it suitable for real-time applications. All nodes can transmit data, ensuring that important information is not lost in the network. Additionally, the rotation of cluster heads helps maintain regular data transmission and can maximize the transmission rate when the network has sufficient energy.

The low-power adaptive clustering protocol still has some disadvantages despite the increased network lifetime and reduced energy usage. In this protocol, it is assumed that every node has the same initial energy (which is often difficult to guarantee in practical deployments). Additionally, this protocol assumes that the nodes are stationary, which makes it challenging to deploy on mobile nodes. Furthermore, the algorithm may not perform optimally in networks with a large number of base stations.

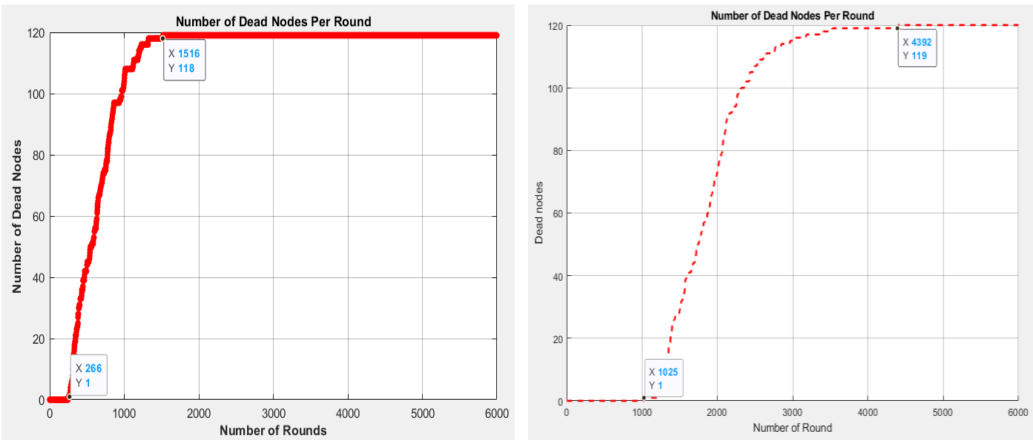


(a) (b)

Figure 7. Number of packets received by the base station per round. (**a**) Low energy adaptive cluster hierarchy method; (**b**) Threshold-based stable CH selection method

Figure 7b shows the communication efficiency of the low-power adaptive clustering protocol and the threshold-based stable CH selection protocol. The results show that the threshold-based stable CH selection method has higher efficiency with a larger and more stable number of packets received by the BS. The set values for the energy level will be used to determine when to collect or transmit data, thus minimizing the use of wasted energy. In addition, the data collection or transmission tasks can be distributed so that the nodes consume as little energy as possible.

The threshold-based stable CH selection protocol aims to minimize the number of network nodes that must transmit data, while limiting unnecessary energy consumption during prolonged data transmissions. This is to improve the network performance (by minimizing the energy consumption of network nodes). The number of dead nodes of the two methods is modeled as shown in Figure 8. Simulation results on MATLAB/Simulink show that the time when the last node died was approximately 3,500 rounds, while the LEACH protocol only maintained about 1,500 rounds.



(a) (b)

Figure 8. Number of dead nodes per round. (**a**) Low-energy adaptive cluster hierarchy method; (b) Threshold-based stable CH selection method.

In the low-energy adaptive cluster hierarchy method, Fig. 8a shows that the number of dead nodes after each round tends to increase almost linearly after the first node dies. However, a number of nodes in the network still maintain a stable operation (between 900 and 1000 rounds), which indicates that the clustering and cluster head selection strategy is highly effective in the early stage.

Simulation results show that the threshold-based stable CH selection protocol (Figure 8b) improves the long-term stability (the first node dies after more than 1000 cycles), improving the network lifetime. In addition, this strategy is energy efficient, while improving the network performance.

The number of dead nodes in a cycle change more slowly (nodes die more gradually) than in low-power adaptive clustering protocols. The even distribution of energy helps maintain network operation for longer periods of time.

5. Conclusions and Future Work

In this paper, we propose a clustering technique for sensor nodes based on the CH selection protocol, which utilizes an energy threshold, and is suitable for small-scale sensor networks. By classifying sensor nodes into three groups according to their energy levels, and implementing a reactive routing mechanism based on the transmission threshold. The main advantages of the proposed method include: reactive communication, three-level heterogeneous energy, and a dynamic cluster head selection mechanism (based on the conditional probability of energy threshold). This method aims to optimize energy efficiency while improving the lifetime of nodes in the network. Simulation results in MATLAB/Simulink demonstrate that the proposed clustering technique not only reduces the dead node ratio but also enhances packet transmission efficiency compared to traditional clustering methods. There are still certain limitations to the current study, however, such as the need to include standard metrics like energy efficiency, first node death, last node death, and packet delivery ratio. Furthermore, a more comprehensive evaluation of the suggested approach is required, encompassing not only the LEACH protocol but also other widely used protocols.

In future studies, the authors plan to extend the evaluation by performing comprehensive benchmarking with other energy-saving protocols and implementing the experimental model on real hardware. This is to verify the feasibility of the proposed method in a real-world deployment context.

In addition, based on a careful assessment of the current challenges, the authors propose several potential future research directions. First, further integrating machine learning algorithms to optimize the CH selection process can increase the network's dynamic adaptability when there are changes in node density or energy levels [31]. Second, studying cluster models combined with lightweight Blockchain to enhance the security and anti-tampering of data during transmission [32], while ensuring integrity and authenticity for wireless sensor networks deployed in sensitive environments, such as healthcare, defense, and smart factories.

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